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Experimental investigation of the thickness effect for large as-welded SAW S355 steel specimens

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Abstract

The presented work aims to investigate and establish a precise, thorough and detailed database from series of experimental testing of submerged arc welded (SAW) specimens of various thicknesses typically applied in ships and offshore structures and foundations. Welded structures of all sizes and shapes exhibit fatigue failure primarily in the welded region, rather than in the base material, due to imperfections and flaws relating to the welding procedure. The welded region has therefore received much attention from universities, research institutions along with industry as it is of significant practical importance for all fatigue loaded structures, such as e.g. marine structures.

Keywords

Welded steel joints, submerged arc welding (SAW), fatigue testing, thickness effect, S-N curves, Standard recommendations

Introduction

As-welded SAW specimens of three different thicknesses, produced by leading industrial manufacturers, were subjected to uni-axial tension loading at relatively high stress-ratios, R , in order to simulate tensile residual stresses of yield magnitude. The main goal was to confirm the thickness effect for the specific case of large transverse butt joints in the as-welded condition as well as to validate whether the thickness correction factor according to recommendations, codes and guidelines is too conservative when it comes to butt-welded joints. A conservative thickness effect factor results in larger, heavier and more expensive structures. The thickness effect considers the influence of the plate thickness on the fatigue resistance of welded joints and is generally included in design rules by scaling the fatigue strength with a recommended factor. The existing database of experiments that relate to the thickness effect is comprehensive and the effect is well proven experimentally and theoretically for various types of welded joints. However, in the case of large butt-welded joints there is room for improvement as details, quality and precise data which can influence the fatigue life of the welded joint is often lacking and severely lacking when consid-

ering truly thick joints.

Motivation for the investigation

Focus was directed towards a known and proven aspect which arises when dealing with very thick structures, namely the thickness effect. In short, it states that as structures become larger their fatigue strength is reduced. Since the investigation considers the idea of manufacturing, assembling and erecting very large wind turbines offshore, the focus area becomes very relevant. The body of guidelines, codes and recommendations has become of age and simultaneously manufacturing processes, material and mechanical properties and design solution have improved. These reasons make the thickness effect a very promising field to investigate.

An investigation of the thickness effect, or size effect, of axially loaded butt welded joints of various thicknesses was performed. A large number of available and relevant experimental fatigue data from literature was assembled into a large database and subjected to a statistical analysis. A total of 1258 experimental data points were collected from over a hundred individual test series, performed at various research institutions and laboratories (Pedersen, et al.; Olafsson, et al., (2016)). The main body of the fatigue test results comes from small scale test specimens. The fatigue tests were all performed at room temperature on fully penetrated butt welded joints in the as-welded condition subjected to tensile loading at a positive stress ratio, $R \geq 0$. The steel material grades ranged from structural S235 up till high strength 960 MPa steel with thicknesses ranging from 8 mm to 100 mm.

In general, the theoretical arguments for the thickness effect are well established and the effect is also proven experimentally for plain steel and many types of welded joints, primarily fillet welded joints. Nonetheless, data for butt welded joints is lacking and severely for thicker joints (Ohta, A et al., (1990))

Fig. 1 below illustrates the collected fatigue test database, plotted along with the recommended fatigue design curve for the respected welded detail, FAT90 (IIW) which corresponds to design S-N curve D (DNVGL). The plot includes scatter bands for the mean ± 2 standard deviation ($P_S = 2.8 - 97.7\%$) calculated using a fixed

slope coefficient of $m = 3.0$ and only using the results from specimens less than or equal to 25 mm thickness, i.e. those which are not subjected to thickness correction and excluding the excessive scatter contribution of the run-out tests.

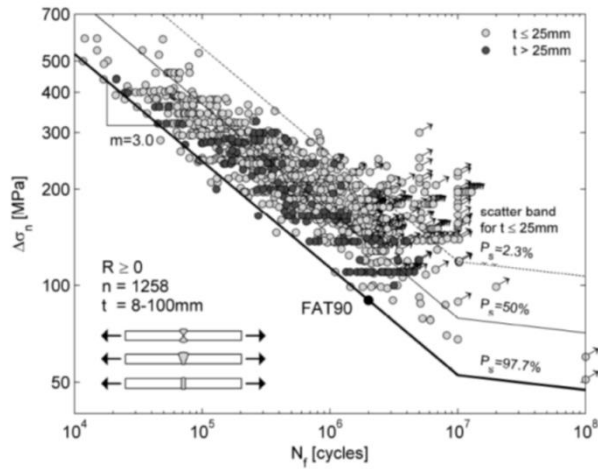


Fig. 1: Fatigue data for butt welded joints of all thicknesses (Pedersen, et al. (2012); Olafsson, et al. (2016))

By excluding of the run-outs, the mean fatigue strength and characteristic fatigue strength are $\Delta\sigma_m = 135.3$ MPa and $\Delta\sigma_c = 90.3$ MPa respectively at 2 million cycles. The FAT90 curve coincides almost completely with the lower bound of the fatigue data points, indicating a good agreement and that a FAT90 slope of 3 is appropriate. Additionally, the figure indicates little difference between thinner specimens (light dots) and thicker specimens (dark dots) and the thicker specimens appear to blend quite well within the scatter band of the thinner specimens (Pedersen, et al., (2012); Olafsson, et al., (2016)).

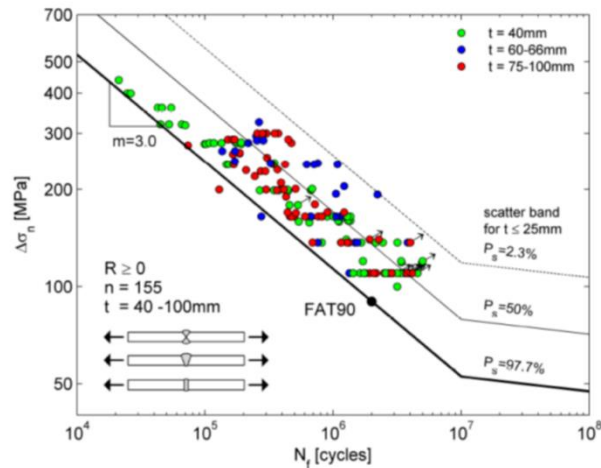


Fig. 2: Fatigue data points for thick welded joints (Pedersen, et al. (2012); Olafsson, et al. (2016))

Figure 2 emphasizes on the test results from the thicker butt welded specimens, i.e. the specimens ranging from 40 mm to 100 mm thicknesses. The data points were grouped into three categories and color coded, green, blue and red for 40 mm, 60-66 mm, and 75-100 mm respectively.

All specimens with thicknesses above 25 mm should be subjected to a thickness correction according to stand-

ards and recommendations. This is applied in design by multiplying the welded joint's designated class and the corresponding fatigue resistance with the following factor:

$$F(t) = \begin{cases} 1 & \text{for } t \leq 25 \text{ mm;} \\ \left(\frac{t_{ref}}{t} \right)^k & \text{for } t > 25 \text{ mm;} \end{cases} \quad (1)$$

The reference thickness, t_{ref} , is usually 25 mm and the suggested exponent, k , varies between design recommendations and has values ranging from 0.1 up to 0.3. The exponent, k , is also dependent on the considered weld detail category, and in the case of butt welded joints in the as-welded condition a value of $k = 0.2$ is recommended (Hobbacher, A.F. (2016); DNVGL, (2014)).

Fig. 2 illustrates a re-calculated mean fatigue strength curve and the corresponding ± 2 standard deviation scatter bands which are calculated from the specimens which are not subjected to thickness correction, i.e. $t \leq 25$ mm. Specimens which ran out along with those which were above the upper scatter band were removed in order to homogenize the population and reduce scatter according to (Hobbacher, A.F. (2016)). From the figure it is evident that there is a tendency of the thicker welded specimens to lie in the lower half of the scatter band. However, there are only 2 specimens lying underneath the lower scatter band and the FAT90 / DNVGL D curve. Moreover, there does not appear to be any obvious variation in fatigue resistance of these larger welded joints. They appear to perform in a relatively equivalent manner, with many occasions where the 75-100 mm thicknesses are outperforming the 40 mm thick specimens, and vice versa.

Taking into account the effects of the thickness correction; a butt welded joint of e.g. 80 mm thickness is subjected to a reduction in fatigue strength from 90 MPa to 71 MPa at 2 million cycles which might be considered on the conservative side based on the collected results from fatigue tests presented in this research.

Motivation for the experimental testing

The results from the literature investigation demonstrated that most of the collected fatigue data results were in good agreement with the recommended design curve. Furthermore, a thickness dependency was observed when comparing the thinner specimens to the thicker ones. However, it can be questioned whether thickness effect and the corresponding thickness correction is as severe as the recommendations suggest for large butt welded joints. Thus, the severity of the thickness effect was called into question and a great incentive was established to continue with the research and commence further experimental study on the matter.

Test preparation

Leading industrial manufactures in Denmark were assigned to produce the specimens which were to be subjected to fatigue testing. Three SAW butt steel plates of

20 mm, 30 mm and 40 mm were ordered in two separate batches.

Material Composition

The applied steel for experimental batches was S355 J2 + N. The material and mechanical properties supplied by the manufactures are listed in Fig. 3-6.

Test Series 1 - Thickness effect of SAW butt joints.																	
Element	C	Si	Mn	P	S	Al	Cu	Cr	Ni	Mo	V	Nb	Ti	N2	As	C _{eq}	
40 mm thick - wt. [%]	0.18	0.35	1.50	0.009	0.006	0.033	0.016	0.015	0.007	0.001	0.002	0.042	0.003	0.0058	-	0.43	
30 mm thick - wt. [%]	0.18	0.27	1.30	0.014	0.007	0.036	0.014	0.02	0.017	0.002	0.02	0.035	0.02	0.0062	0.003	0.41	
20 mm thick - wt. [%]	0.15	0.43	1.40	0.009	0.005	0.029	0.07	0.06	0.04	0.007	0.003	0.034	0.012	0.009	0.0038	-	

Fig. 3: Batch 1. Material composition (Olafsson, et al. (2016))

Test Series 1 - Thickness effect of SAW butt joints.								
Cast No	Test No	Plate No	Thickness [mm]	Width [mm]	Length [mm]	Yield strength [Mpa]	Tensile strength [MPa]	Elongation [%]
44123B1	-	3315F-1-1	40	3000	10000	381	536	25
Y921121	8488	253240	30	3000	12000	406	558	25
V25848	6860	12	20	2500	8000	370	510	32

Fig. 4: Batch 1. Mechanical properties (Olafsson, et al. (2016))

Test Series 1 - Thickness effect of SAW butt joints.																	
Element	C	Si	Mn	P	S	Al	Cu	Cr	Ni	Mo	V	Nb	Ti	N	C _{eq}		
40 mm thick - wt. [%]	0.15	0.52	1.44	0.019	0.003	0.033	0.04	0.04	0.04	0.01	0.00	0.025	0.005	0.0045	0.41		
30 mm thick - wt. [%]	0.16	0.49	1.44	0.014	0.002	0.041	0.02	0.04	0.03	0.01	0.00	0.026	0.005	0.0035	0.41		
20 mm thick - wt. [%]	0.18	0.31	1.47	0.016	0.003	0.022	0.001	0.05	.01	0.002	0.007	0.022	0.012	0.0023	0.44		

Fig. 5: Batch 2. Material composition (Olafsson, et al. (2016))

Test Series 1 - Thickness effect of SAW butt joints.								
Cast No	Test No	Plate No	Thickness [mm]	Width [mm]	Length [mm]	Yield strength [Mpa]	Tensile strength [MPa]	Elongation [%]
640639	-	715844/1/3	40	2000	12000	371	534	33,5
642799	-	720657/1/7	30	2000	12000	402	545	30,5
011361	-	1258-01248	20	4000	16000	435	575	28,5

Fig. 6: Batch 2. Mechanical properties (Olafsson, et al. (2016))

Welding procedure

The welding method applied was semi-automatic submerged arc welding (SAW), as it is accountable for most welds relating to offshore structures. Instructions were given to the operators that the welding process should focus with great emphasis on restraining the axial and angular misalignment. Additionally, the operator should make sure that there is no stopping and re-starting during the welding process and the same operator was hired to perform the entire welding procedure for all the requested steel plates.

The butt welded plates were manufactured according to the details in Fig. 7 and Fig. 8. The SAW butt plates from batch 1 had 4, 7 and 9 passes for the 20 mm, 30 mm and 40 mm thick plates respectively. The SAW butt plates from batch 2 had 4, 8 and 10 passes for the 20 mm, 30 mm and 40 mm thick plates respectively. Welding repairs had to be made on the 30 mm and 40 mm plates from batch 2. However, the specimens cut from the repaired regions were primarily used for static testing or not at all for the 40 mm thicknesses (Olafsson, et al., (2016)).

Test Series 1 - Thickness effect of SAW butt joints.			
-	20 mm thick	30 mm thick	40 mm thick
Process	SAW	SAW	SAW
Weld length	1500 mm	1500 mm	1500 mm
Consumable	ESAB OK 12.22	ESAB OK 12.22	ESAB OK 12.22
Flux	ESAB OK 10.72	ESAB OK 10.72	ESAB OK 10.72
Position	PA Flat	PA Flat	PA Flat
Geometry	X-groove	X-groove	X-groove
Nose	3 mm	3 mm	3 mm
Edges	2 x 37.5°	2 x 37.5°	2 x 37.5°
Polarization	DC+ / AC	DC+ / AC	DC+ / AC
Current	350 - 750 A	400 - 800 A	400 - 825 A
Speed	26 - 53 cm/min	39 - 60 cm/min	35 - 65 cm/min
Arc voltage	24 - 38 V	23 - 38 V	24 - 38 V
Heat input	-	-	-
Preheating	-	-	-
Interpass temperature	20 - 50°C	20 - 110°C	20 - 115°C
Weld passes	4 (3 and 1)	7 (4 and 3)	9 (5 and 4)
Repair	No	No	No
Repair passes	-	-	-

Fig. 7: Batch 1. Welding procedure (Olafsson, et al. (2016))

Test Series 1 and 2 - Thickness effect of SAW butt joints.				
-	20 mm thick (air)	20 mm thick (seawater)	30 mm thick	40 mm thick
Process	SAW	SAW	SAW	SAW
Weld length	1800 mm	1800	1800 mm	1800 mm
Consumable	ESAB OK 12.22	ESAB OK 12.22	ESAB OK 12.22	ESAB OK 12.22
Flux	ESAB OK 10.72	ESAB OK 10.72	ESAB OK 10.72	ESAB OK 10.72
Position	PA Flat	PA Flat	PA Flat	PA Flat
Geometry	X-groove	X-groove	X-groove	X-groove
Nose	-	-	-	-
Edges	-	-	-	-
Polarization	DC+ / AC	DC+ / AC	DC+ / AC	DC+ / AC
Current	350 - 750 A	350 - 750 A	400 - 800 A	400 - 825 A
Speed	26 - 53 cm/min	26 - 53 cm/min	39 - 60 cm/min	35 - 65 cm/min
Arc voltage	24 - 38 V	24 - 38 V	23 - 38 V	24 - 38 V
Heat input	1,1 - 2,8 KJ/min	1,1 - 2,8 KJ/min	1,5 - 2,9 KJ/min	1,4 - 3,0 KJ/min
Preheating	-	-	-	-
Interpass temperature	20 - 50°C	20 - 110°C	20 - 115°C	20 - 115°C
Weld passes	4	4	8 (5 and 3)	10 (5 and 5)
Repair	No	No	Yes (2)	Yes (1)
Repair passes	-	-	20 and 20	27

Fig. 8: Batch 2. Welding procedure (Olafsson, et al. (2016))

Non destructive testing

All SAW butt joints were subjected to non destructive testing in order to verify that the weld quality demands are accepted to specifications. Fig. 9, lists all performed NDT's for batch 1 and batch 2 respectively.

Defects were detected by ultrasonic testing of the 20 mm thick welded plate from batch 1 and the 30 mm and 40 mm thick plates from batch 2. All defected welds were repaired and the plates were re-subjected to NDT and passed examination without any remarks (Olafsson, et al., (2016)).

Test Series 1 - Thickness effect of SAW butt joints.				
	Thickness [mm]	Visual inspection	Ultrasonic testing / after repair	Magnetic particle testing
Batch 1	20	✓	Defect 40 mm from edge, depth 10-13 mm / ✓	✓
	30	✓	✓	✓
	40	✓	✓	✓
Batch 2	20	✓	✓	✓
	30	✓	Defected, 40-110 mm & 710-830 mm / ✓	✓
	40	✓	Defected, 0-520 mm / ✓	✓

Fig. 9: Non destructive testing of all welded joints (Olafsson, et al. (2016))

Cutting procedure

The cutting procedure was performed with a water-jet cutting machine. The cutting technique results in a good, smooth and accurate cut with no heat distortion which can have a significant effect on the specimens, according to ESAB (Olafsson, et al., (2016)).

The first batch was cut down into straight test specimens while the second batch was cut down into tensile dog-bone shaped test specimens, illustrated in Fig.10.

Following the cutting procedure, the specimens were cleaned and coated with media to prevent corrosion of the steel material. All specimens were labelled in order to keep track of their original location within the welded plate. Lastly, all specimens were covered for storage.

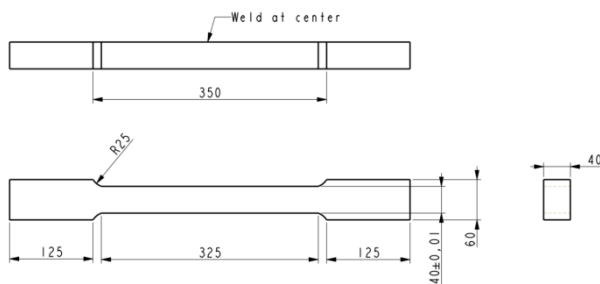


Fig. 10: SAW butt specimen dimensions (Olafsson, et al. (2016))

Equipment

The static testing was performed in a 2MN MLF static testing machine and a 500 kN MTS servo hydraulic testing machine.

The fatigue test series were performed in several servo hydraulic testing machines, i.e. a 500 kN MTS, 500 kN Instron and a 1 MN Instron.

All servo hydraulic testing machines were calibrated before initiating the test series. The load cells and the applied measurement equipment were verified before starting (Olafsson, et al., (2016)).

Experimental testing

Static testing

The butt welded joints were subjected to axial static testing in order to obtain their mechanical properties, verify the manufacturers yield strengths and most importantly estimate a reference load level for the subsequent fatigue testing. The static tensile testing was performed in accordance to ASTM E8, ASTM E111 and DS/EN ISO 6892.

The static testing was mainly performed in order to retrieve adequate load levels for the subsequent fatigue testing of butt welded joints cut from the same welded plate. Additionally, verifying and validating that the material was of the desired strength and that the weld was made according to specifications and able to withstand these high tensile loads. The static testing rate varied from 1-4 mm per minute (Olafsson, et al.,

(2016)).

Fatigue testing

The fatigue test series was performed on as-welded SAW butt joints of three different thicknesses, i.e. 20 mm, 30 mm and 40 mm. The specimens were subjected to constant amplitude sinusoidal waveform at frequencies ranging from 6-10 Hz. Testing was based on the estimated yield strength of the SAW butt welded joints from the static test results. The cyclic loading was performed at a stress ratio of $R = 0.5$, with stress levels calculated as a percentage of the specimens average yield strength, σ_y . Additionally, in order to generate a reliable S-N curve, the welded joints were tested at a minimum of five different stress levels and with a minimum of five specimens tested at each stress level. The fatigue threshold limit was 5 million cycles. All tests were carried out in laboratory air conditions at room temperature, $+20^\circ\text{C}$. The definition of failure in all fatigue tests was complete rupture, which is commonly very near the through thickness cracking (Olafsson, et al., (2016)).

The testing at stress levels calculated as a percentage of the average yield strength of the respective thickness was performed in order to minimize the potential differences of residual stresses, which can vary quite significantly between thicknesses.

The choice of $R = 0.5$ was decided after considering the affects of residual stresses, in order to better simulate the high tensile residual stresses experienced by welded joints in real large structures (Ohta, A. et al., (1990)). In this way, it would be possible to mimic as close as possible the actual loading conditions experienced by a monopile structure and maximizing the possibility for a comparison to existing structural results. Taking into account the recommendations from IIW, for generating a proper S-N fatigue curves, close attention has to be brought on to the fact that internal stresses are usually lower in small scale specimens. IIW states that results from these small scale testing should be rectified in order to take into account the greater effects of residual stresses in structures, therefore representing the real situation at hand. In order to achieve these more realized values, IIW recommends testing at high stress ratios, R , e.g. $R = 0.5$, or by applying a stress ratio of $R = 0$ followed by a 20% reduction of fatigue strength at 2 million cycles (Hobbacher, A.F. (2016)).

Additionally, there is a notable lack of experimental test results in literature of butt welded joints tested at $R = 0.5$.

Test results

Static testing

All statically loaded specimens fractured in the base material, as the welded region was over-matched, i.e. made of a material of higher strength. Furthermore, all specimens broke far from the weld region and the heat affected zone. The mechanical properties are listed in Fig. 11 and Fig. 12. The yield levels were estimated by

applying a 0.2% offset curve.

Specimen #	Width [mm]	Thickness [mm]	Area [mm ²]	Length [mm]	σ_y [MPa]	σ_{ult} [MPa]	E modulus [GPa]
T20.1	20.11	20.65	415.27	500	361.37	524.81	211.65
T20.2	20.10	20.64	414.86	500	377.93	518.16	208.58
T20.3	20.13	20.67	415.88	500	378.02	520.99	206.18
T20.35	20.07	20.36	408.63	500	376.32	521.17	202.91
T20.36	20.13	20.38	410.25	500	373.78	523.91	205.78
T30.1	20.12	30.29	609.43	500	350.23	517.36	205.43
T30.2	20.31	30.35	616.41	500	374.19	511.04	197.76
T30.3	20.29	30.38	616.31	500	377.83	510.32	201.59
T30.35	20.33	30.37	617.42	500	379.93	509.16	211.88
T30.36	20.17	30.39	612.97	500	375.29	512.88	190.71
T40.1	20.11	40.52	814.05	500	355.30	534.50	203.82
T40.2	20.17	40.58	818.50	500	367.92	526.50	209.34
T40.3	20.15	40.52	816.38	500	371.52	527.27	189.40
T40.35	20.19	40.53	818.20	500	368.07	526.74	188.24
T40.36	20.17	40.53	817.49	500	345.81	525.60	195.26

Fig. 11: Mechanical properties from batch 1 (Olafsson, et al. (2016))

Specimen #	Width [mm]	Thickness [mm]	Area [mm ²]	Length [mm]	σ_y [MPa]	σ_{ult} [MPa]	E modulus [GPa]
T20.1.1	39.82	19.87	791.22	600	407.88	543.57	198.37
T20.1.2	39.86	19.89	792.65	600	406.27	548.05	194.14
T20.26.1	39.72	19.78	785.47	600	416.15	548.15	190.90
T20.26.2	39.79	19.78	787.19	600	391.39	-	214.87
T20.27.2	39.77	19.79	787.05	600	410.30	-	216.29
T30.1.2	39.82	30.17	1201.70	500	365.70	519.64	210.77
T30.2.2	39.73	30.16	1198.06	500	372.82	515.98	210.88
T30.3.2	39.65	30.31	1201.59	500	375.68	538.30	206.91
T40.19.2	39.77	40.19	1598.36	500	358.36	522.24	194.90
T40.20.2	39.67	40.39	1601.87	500	354.55	522.60	191.69
T40.22.2	39.70	40.26	1597.92	500	354.80	522.45	192.32
T40.23.2	39.80	40.31	1604.14	500	358.40	522.56	183.07
T40.24.2	39.65	40.25	1595.71	500	357.66	526.07	189.44

Fig. 12: Mechanical properties from batch 2 (Olafsson, et al. (2016))

Fatigue testing

The test series started with the fatigue testing of the 20 mm thick specimens. The results from these initial tests will serve as a reference for the subsequent testing as butt welded components with less than 25 mm wall thicknesses are not subjected to a thickness correction according to recommendations.

The fatigue test sequence started with testing the specimens with stress ranging from $\sigma_{max} = \sigma_y$ at $R = 0.5$. Thereafter the stress level was calculated as a percentage of the average yield strength until a fatigue threshold limit was reached. The results from the 20 mm thick specimens are illustrated in Fig. 13.

Fig. 13, illustrates the fatigue test results from the 20 mm specimens with the stress range, $\Delta\sigma$, on the ordinate

and cycles to failure, N , on the abscissa. Additionally, a mean curve is shown along with ± 2 standard deviation scatter bands from the mean, which corresponds to a survival probability of 97.7%.

The figure illustrates the five different stress levels, where specimens are running out, i.e. reaching 5 million cycles, at the two lowermost stress ranges. All fatigue test results lie within the ± 2 standard deviation scatter bands from the mean.

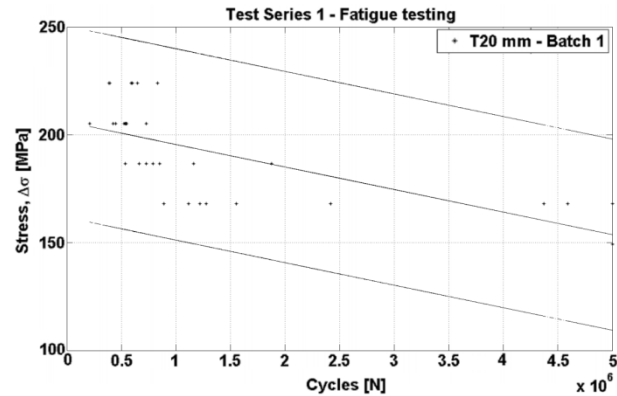


Fig. 13: Fatigue test results for the 20 mm thick specimens from batch 1. (Olafsson, et al. (2016))

Fig. 14, illustrates a combined plot after inserting the fatigue test results from the 30 mm and 40 mm thick specimens from batch 1, excluding those who fractured in the grip region. The mean curve and ± 2 standard deviation scatter bands are solely calculated from the specimens not subjected to thickness correction, i.e. the 20 mm thick specimens. Additionally, all specimens that reached the threshold limit were excluded from the mean curve calculation as they show superior fatigue resistance and contribute extensively to the scatter of the data.

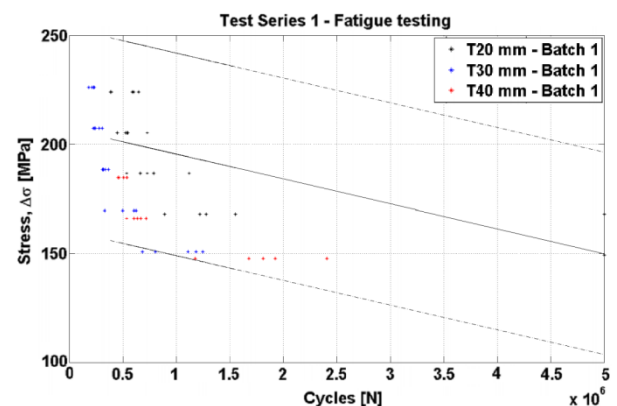


Fig. 14: Fatigue test results for all three thicknesses from batch 1, excluding specimens that fractured in the grip region (Olafsson, et al. (2016))

Fig. 15, illustrates the fatigue test results plotted with the recommended design S-N curve on a log-log graph for the respective structural detail, i.e. butt welded joints in the as-welded condition. That corresponds to FAT90 according to IIW and to design curve D in the DNVGL recommendations, which is interpreted as the allowable design stress equaling 90 MPa at 2 million cycles.

Fig. 15, illustrates that all fatigue specimens tested lie above the recommended design curve, FAT90. The design curve itself also appears to be a good and valid recommendation as all specimens are scattered above the curve. There is a single test specimen of the 30 mm thick joints which comes close to the design curve, while all the 40 mm thick test results are located safely above the design curve.

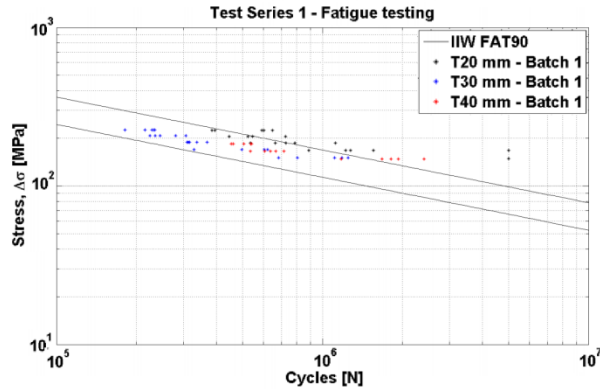


Fig. 15: Fatigue results for all three thicknesses from batch 1, including the recommended fatigue design S-N curve, FAT90. (Olafsson, et al. (2016))

However, the 30 mm and 40 mm thick specimens are to be subjected to thickness correction, which means that the design stress range should be lowered for the same number of cycles endured, i.e. their fatigue resistance is reduced. The recommended thickness correction design curves for the 30 mm and 40 mm thick specimens are illustrated in Fig. 16.

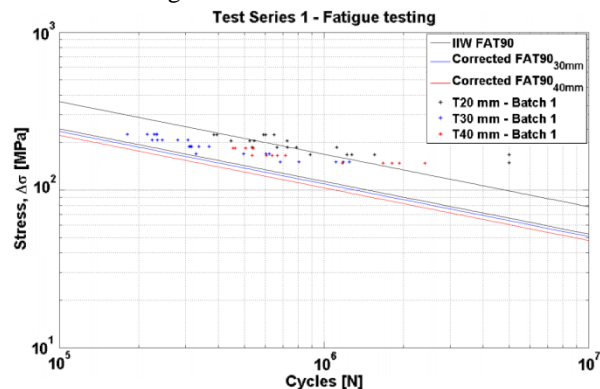


Fig. 16: Fatigue test results for all three thicknesses from batch 1, including the original and thickness corrected recommended fatigue design curves, FAT90. (Olafsson, et al. (2016))

Fig. 16, illustrates that the thickness correction recommendation for the 30 mm thick specimens appears to be a decent recommendation as there was a specimen which fractured close to the FAT90 curve and the correction corresponds to a stress range reduction of 6 MPa. However, more interestingly the corrected curve for the 40 mm thick specimens appears to be an overly conservative measure, reducing the recommended design fatigue strength by 13 MPa or approximately 9.29%. Furthermore, the resulting fracture from the 40 mm thick specimens which was closest to the original FAT90 curve is 26.1 MPa above the curve, or approximately 18.64%. Comparing the same 40 mm thick spec-

imen to the corrected FAT90 design curve for the 40 mm thick welded joints, it lies 39.1 MPa above the curve, or approximately 30.79%.

By inserting the fatigue test results from batch 2 the experimental investigation was given increased weight and more validity.

Fig. 17, illustrates the total test population after adding the additional fatigue test results from batch 2 into the previous log-log plot from batch 1 along with the original and corrected design S-N curves. The mean curve was adjusted to the additional population of 20 mm thick specimens.

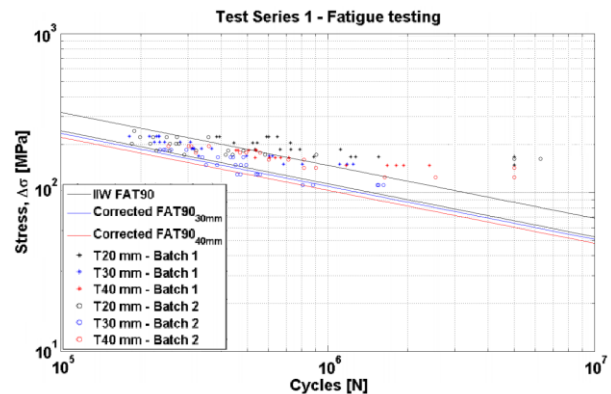


Fig. 17: Fatigue test results for all three thicknesses from batch 1 and batch 2, including the original and thickness corrected recommended fatigue design curve, FAT90 (Olafsson, et al. (2016))

Fig. 17, illustrates that the SAW butt specimens from batch 2 have an overall lower fatigue resistance compared to batch 1, even though the previous welding procedure was replicated. This demonstrates to a high degree the variability of the welding procedure and the difficulty of manufacturing a welded joint with high quality and repeatability. Therefore, another angle concerning weld quality effect was added to the investigation.

Fig. 17, illustrates however a similar trend as observed from batch 1. All but a single specimen for the 20 mm thickness lie above the recommended design S-N curve. The 30 mm thick specimens demonstrate less fatigue resistance and a total of nine specimens lie on or below the recommended curve, as well as the corrected S-N curve for the 30 mm thickness. However, when considering the 40 mm thick specimens, they exhibit higher fatigue strength than both the 20 mm and the 30 mm thick specimens and lie comfortably above the original recommended design S-N curve for specimens not subjected to thickness correction. The 40 mm thick specimen which is closest to the original curve is 12.4 MPa above, or approximately 7.47%. Additionally, this same specimen is 27.4 MPa above the thickness corrected design curve for the 40 mm thick specimens, or approximately 18.15% (Olafsson, et al., (2016)).

Summary

The results from the performed literature review gave a basis for further investigation of the thickness effect of

SAW butt joints. From the acquired collection of data, the larger welded joints, ≥ 25 mm, were located primarily within the ± 2 standard deviations of the scatter bands from the mean results calculated for the under 25 mm thick specimens, which are not subjected to a thickness correction. However, the thicker specimens did collect in the lower half of the scatter band, which coincidentally coincided with the recommended design S-N curve for this specific welded detail, i.e. butt welded joints. Another particularly interesting observation was that the extremely thick welded joints had similar fatigue strengths compared to the lower thicknesses.

Thus, an indication of the thickness effect was observed, however the magnitude of the fatigue strength reduction due to thickness was not as severe as the standards and guidelines recommend.

Subsequently the performed experimental fatigue testing of SAW butt joints demonstrated a similar tendency. The 20 mm thick specimens demonstrated the highest fatigue resistance when compared directly to the 30 mm and 40 mm thick joints. However, almost the entire population of the larger joints tested until fracture were located within the lower scatter band of the ± 2 standard deviations calculated from the mean results from the 20 mm thick specimens. Furthermore, the 40 mm thick specimens demonstrated improved fatigue resistance when compared to the 30 mm thick specimens (Olafsson, et al., (2016)).

Conclusions

The fatigue test series investigated the effect of thickness on the fatigue resistance of SAW butt joints. The results demonstrated the presence of a thickness effect as the thicker SAW butt joints had reduced fatigue resistance. However, the significance of the observed thickness effect was not as detrimental as the current standards and guidelines recommend for the design of welded structures. Therefore, the results indicate a possibility of revising the current recommendations concerning the thickness effect correction factor (Olafsson, et al., (2016)).

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